Constraints on Gravity and Dark Matter from Clusters of Galaxies

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MOND was developed by Milgrom (1983) to explain the rotation curves of spiral galaxies without needing dark matter.

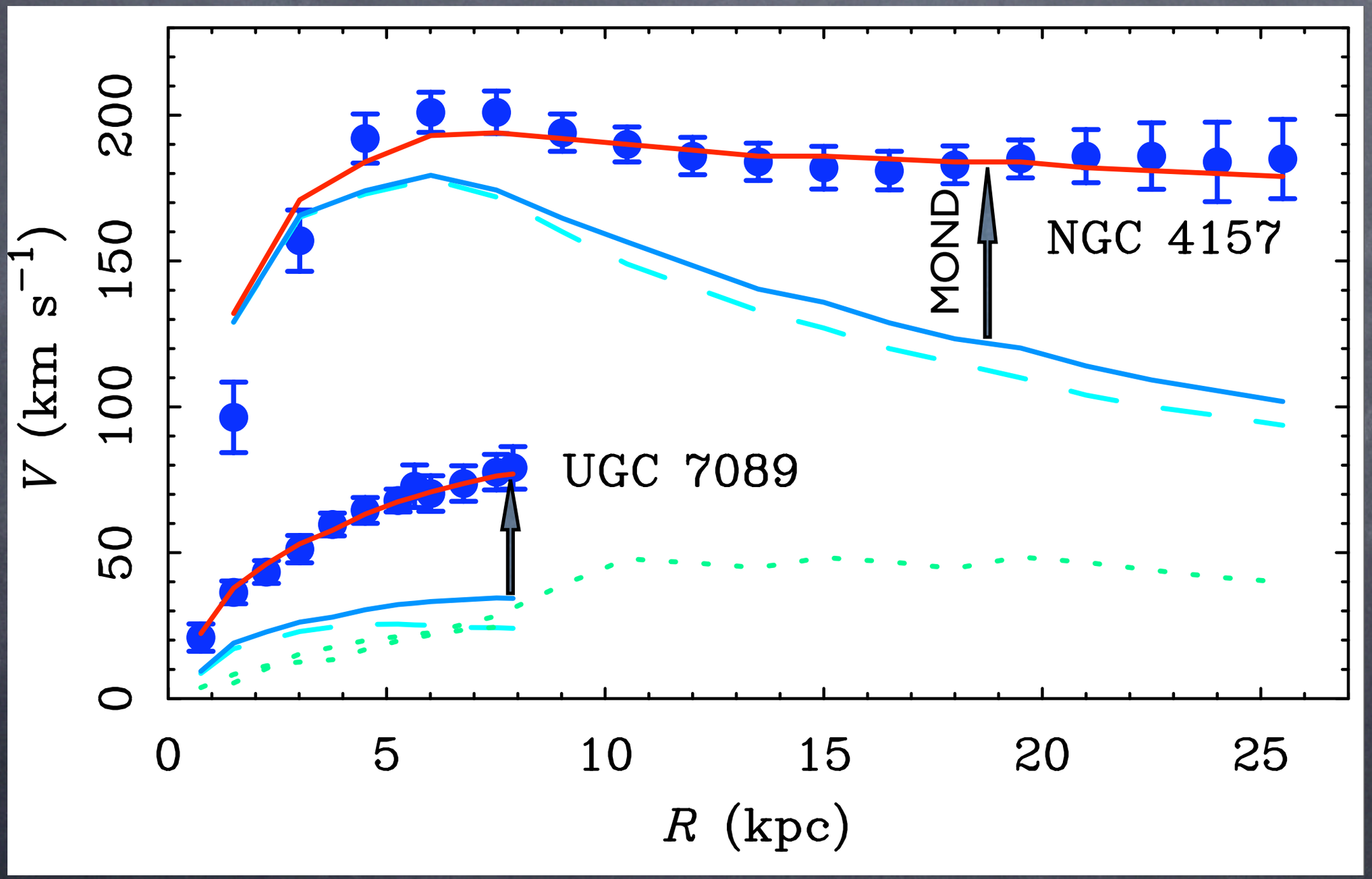


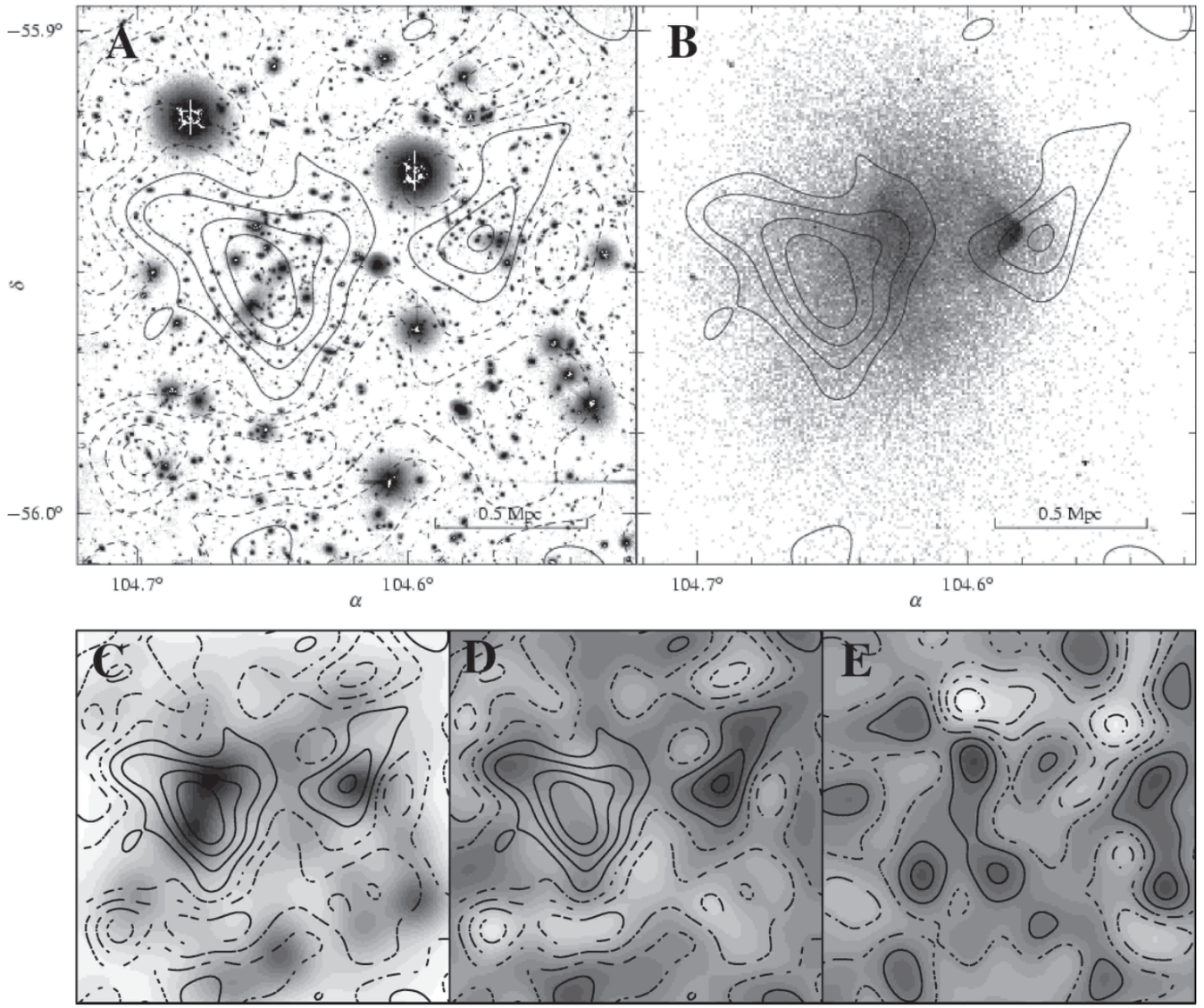
Figure stolen from Stacy McGaugh

It does that very well!

MOND fails with clusters of galaxies

- Sanders (2003) found that galaxies + X-ray plasma was not sufficient with MOND to explain the X-ray temperature
- Suggested a massive (~2 eV) neutrino to make up the missing mass
- This would not harm MOND's fits to spiral galaxies, as the 2 eV neutrino's density profile has a large core in a typical spiral galaxy potential

The Bullet Cluster (v 1.0)

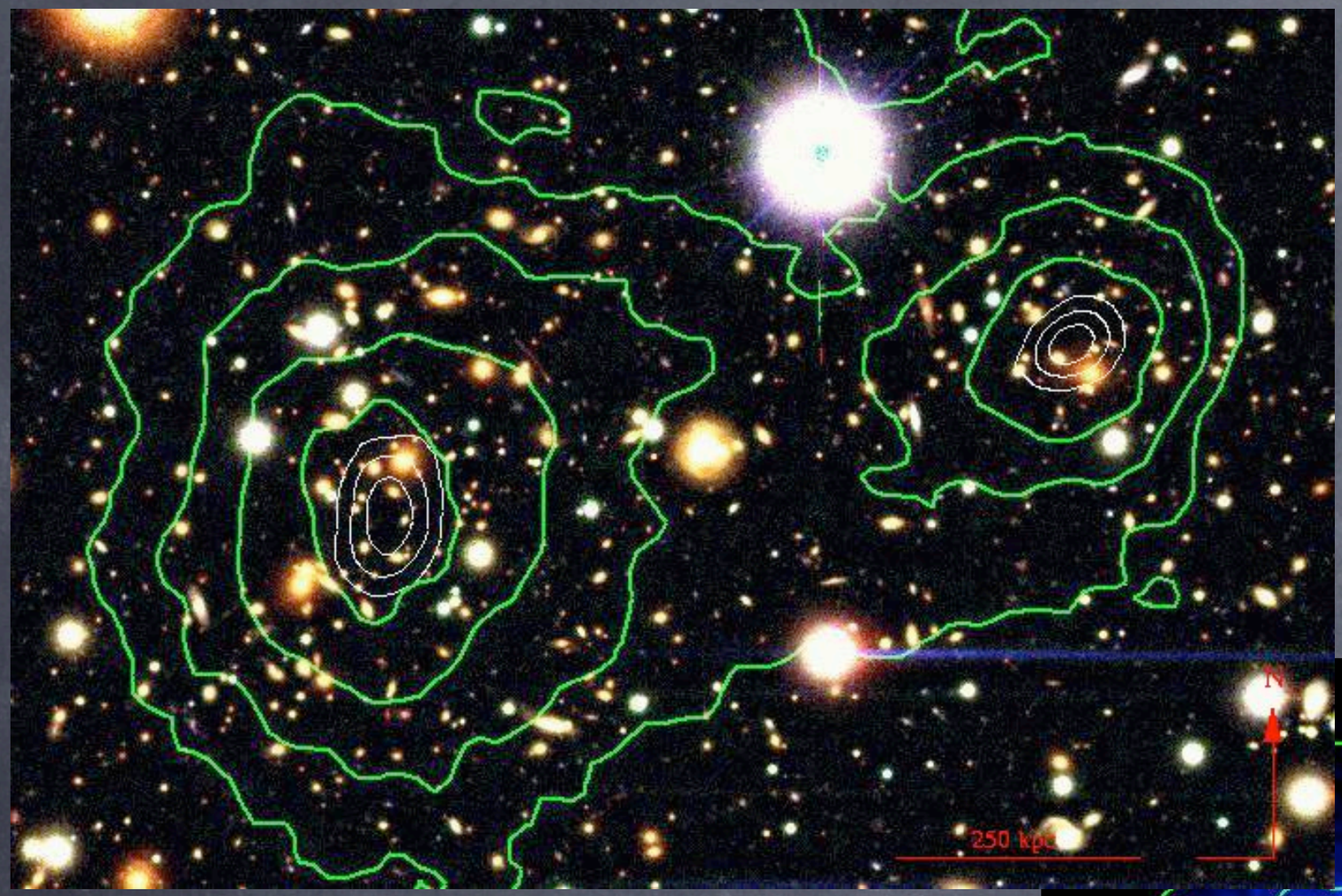


Weak lensing gravity centroids offset from the plasma centroids by 2-3

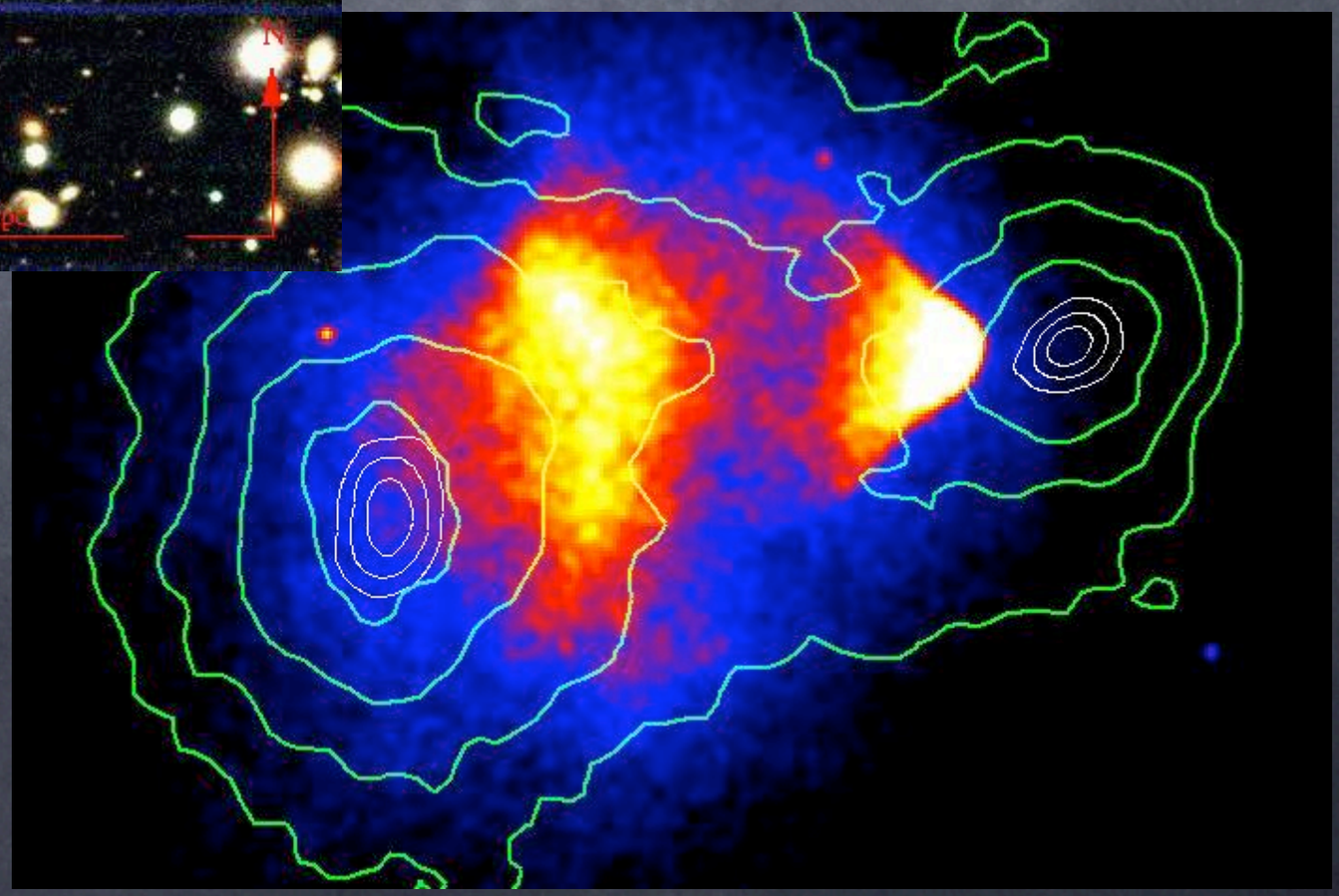
X-ray refinements

- Pointecouteau and Silk (2005) looked at 10 clusters to large radial range (>0.5 R_{200}) with XMM
- Modeling with MOND required 4 times the amount of mass in a dark component compared with the X-ray plasma
- Still (barely) viable with a 2 eV neutrino

The Bullet Cluster (v 1.1)



Conclusion: in any modified gravity, you will need at least twice as much DM as visible baryons

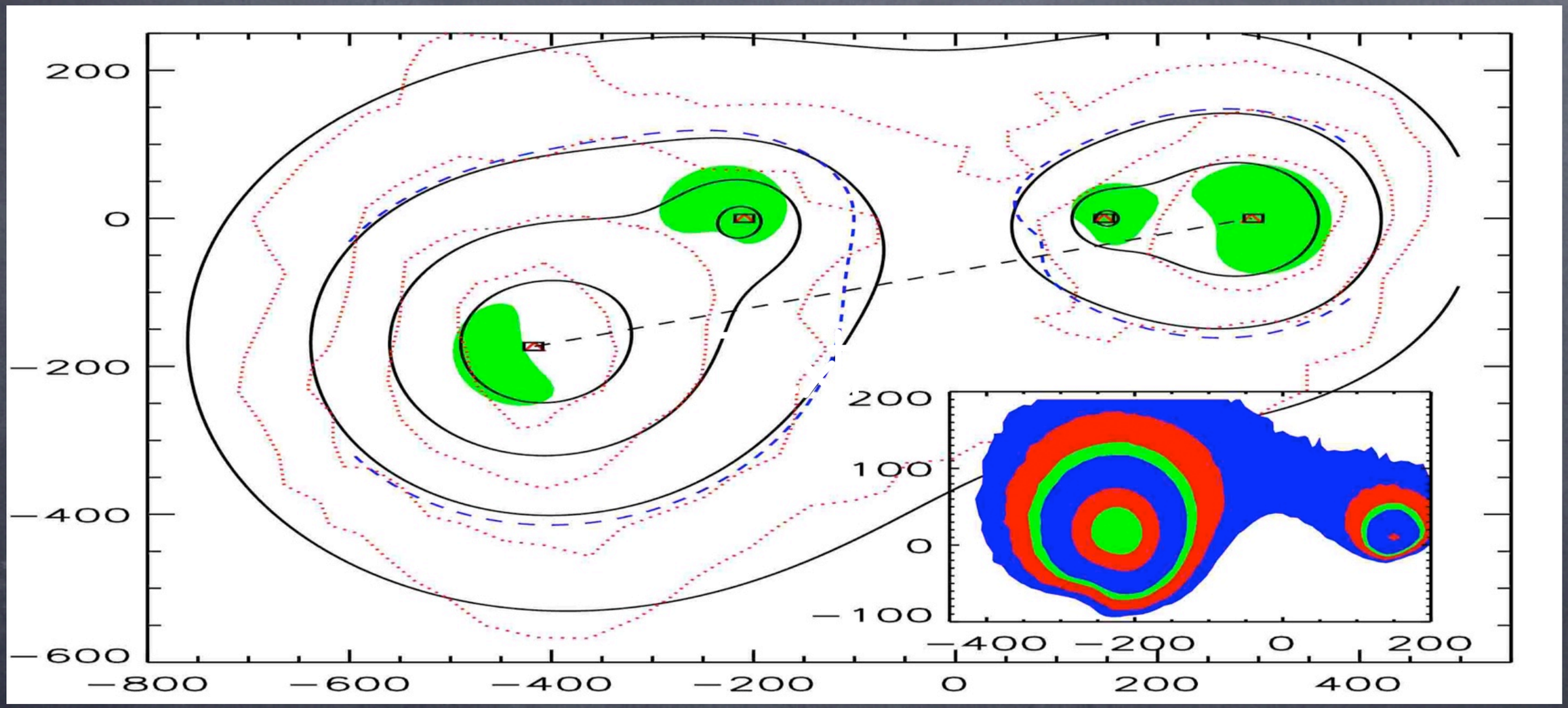


green = convergence
white = centroid errors

Clowe et al (2006)

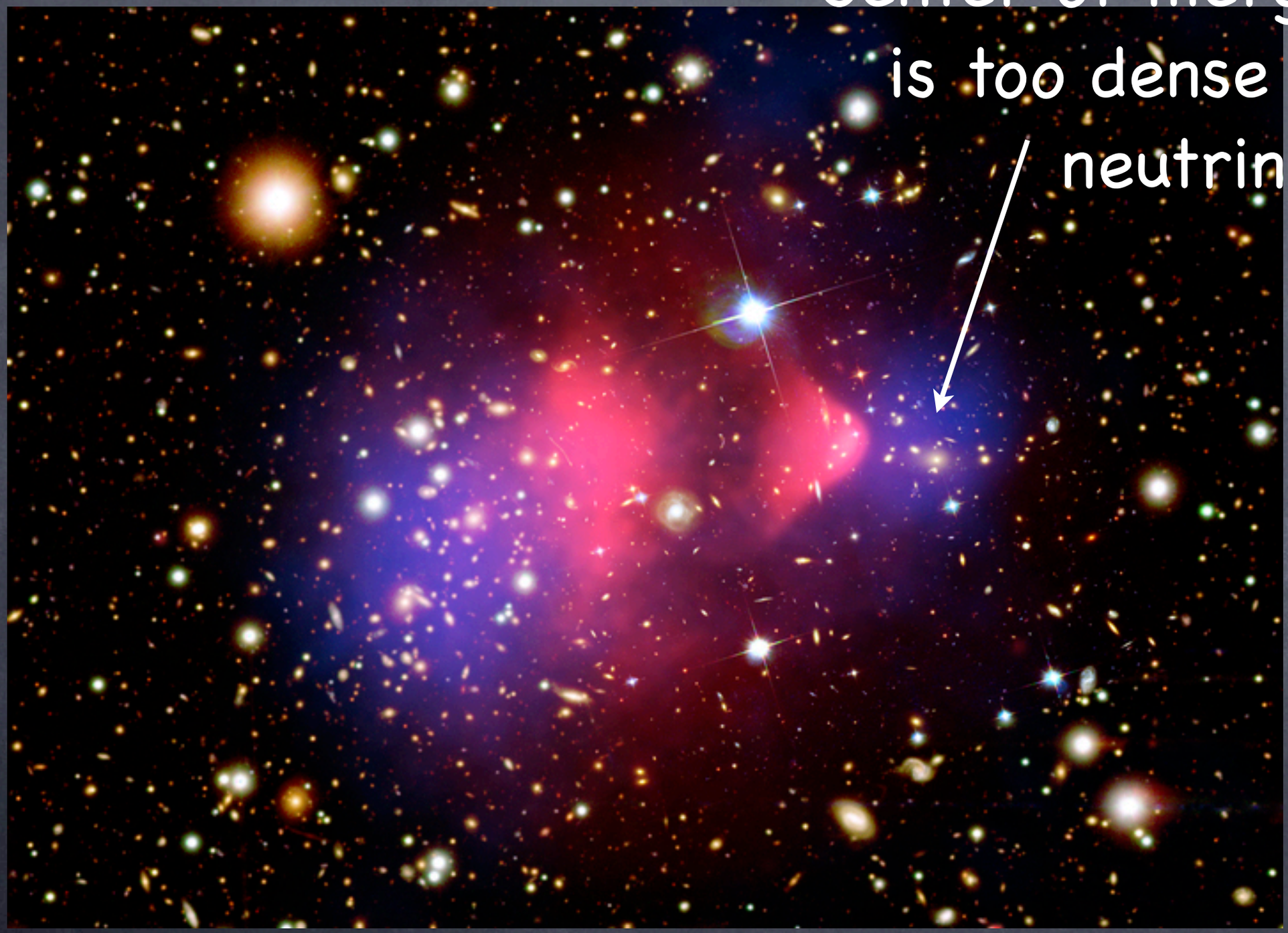
TeVeS Model

Angus et al 2006, ApJ, 654, L13



See also Feix, Fedeli, and Bartelmann 2007

Center of merging bullet is too dense for 2eV neutrinos!



red = X-ray plasma

blue = weak lensing convergence

Merger Velocity Problem?

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- Shock velocity not affected by gravity (Milos[2] et al), X-ray gas moving toward bullet (Springel & Farrar) -> true velocity 3000-3500 km/s

MOND vs DM

~~MOND~~ vs DM

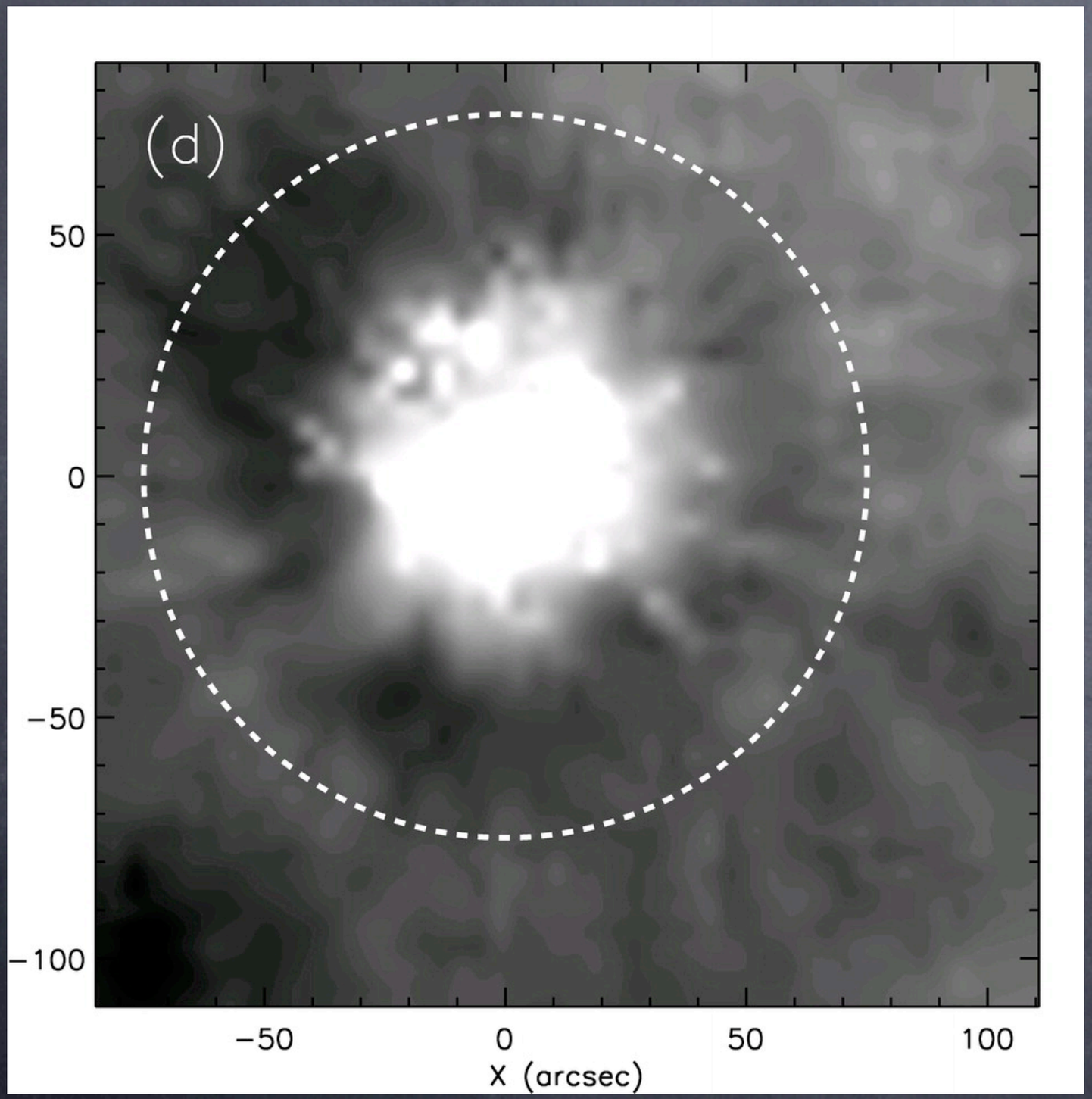
~~MOND~~ vs DM

MOND + WDM

vs

CDM

CL0024 DM "Ring"



Jee et al (2007)

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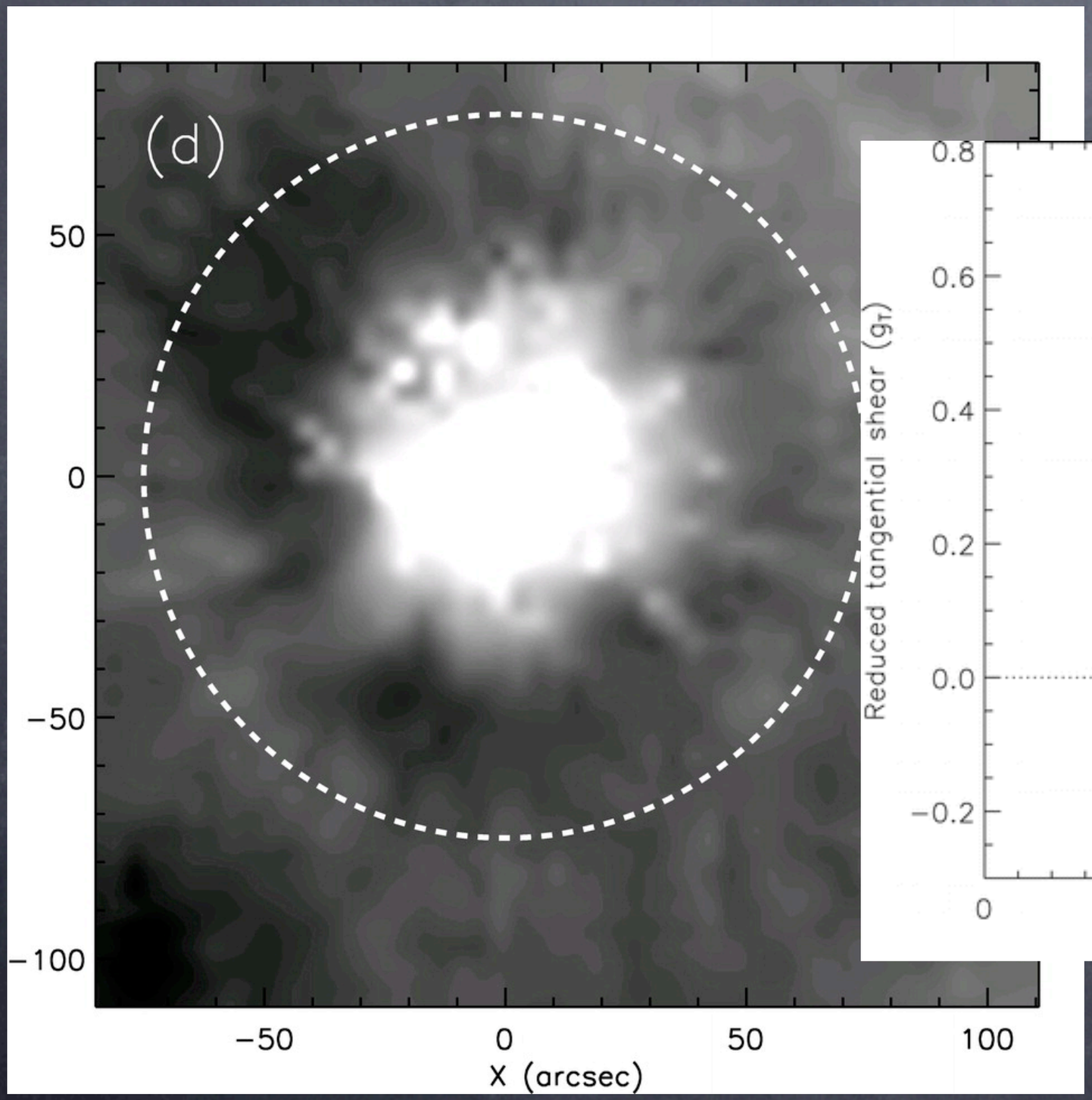

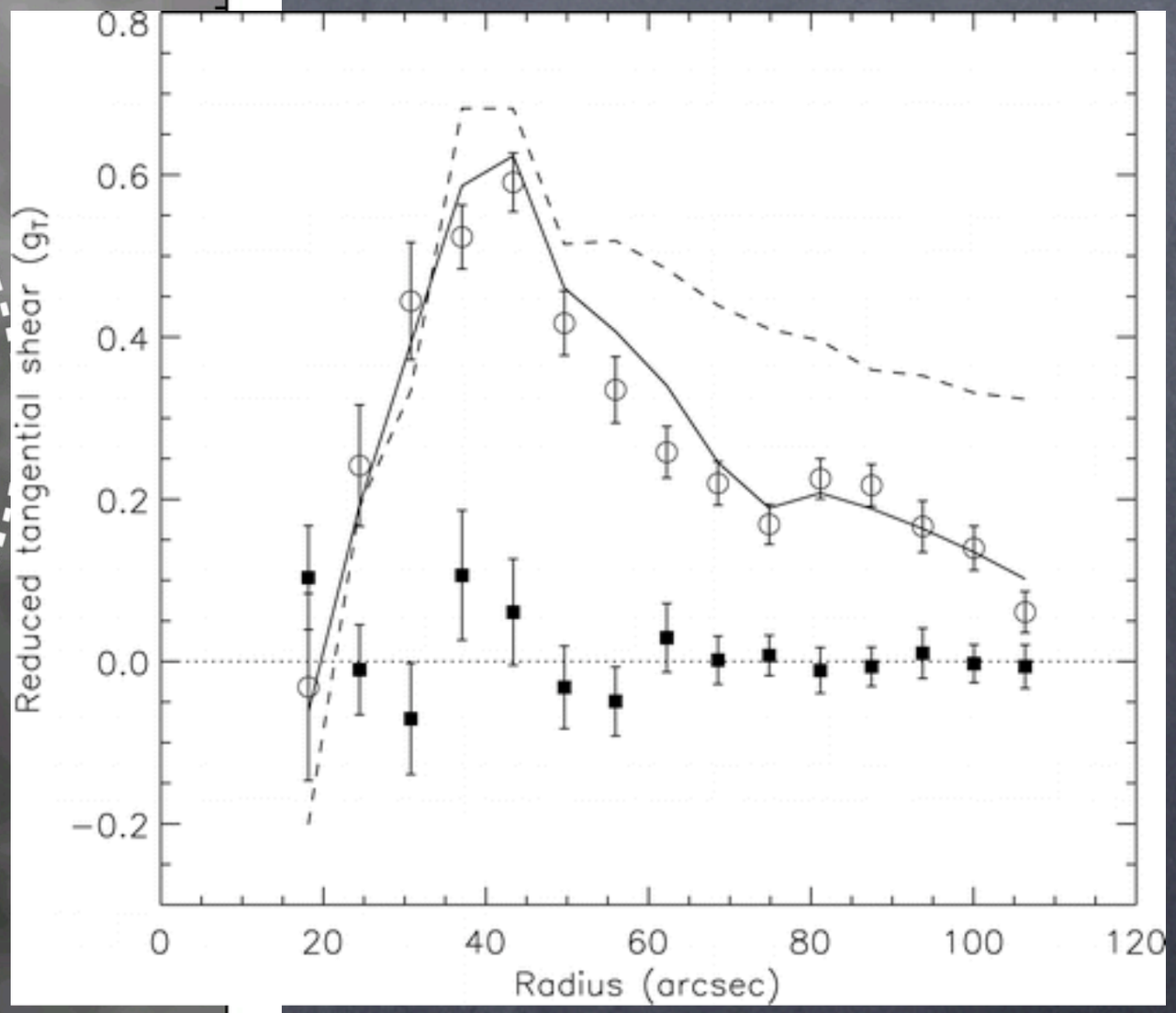

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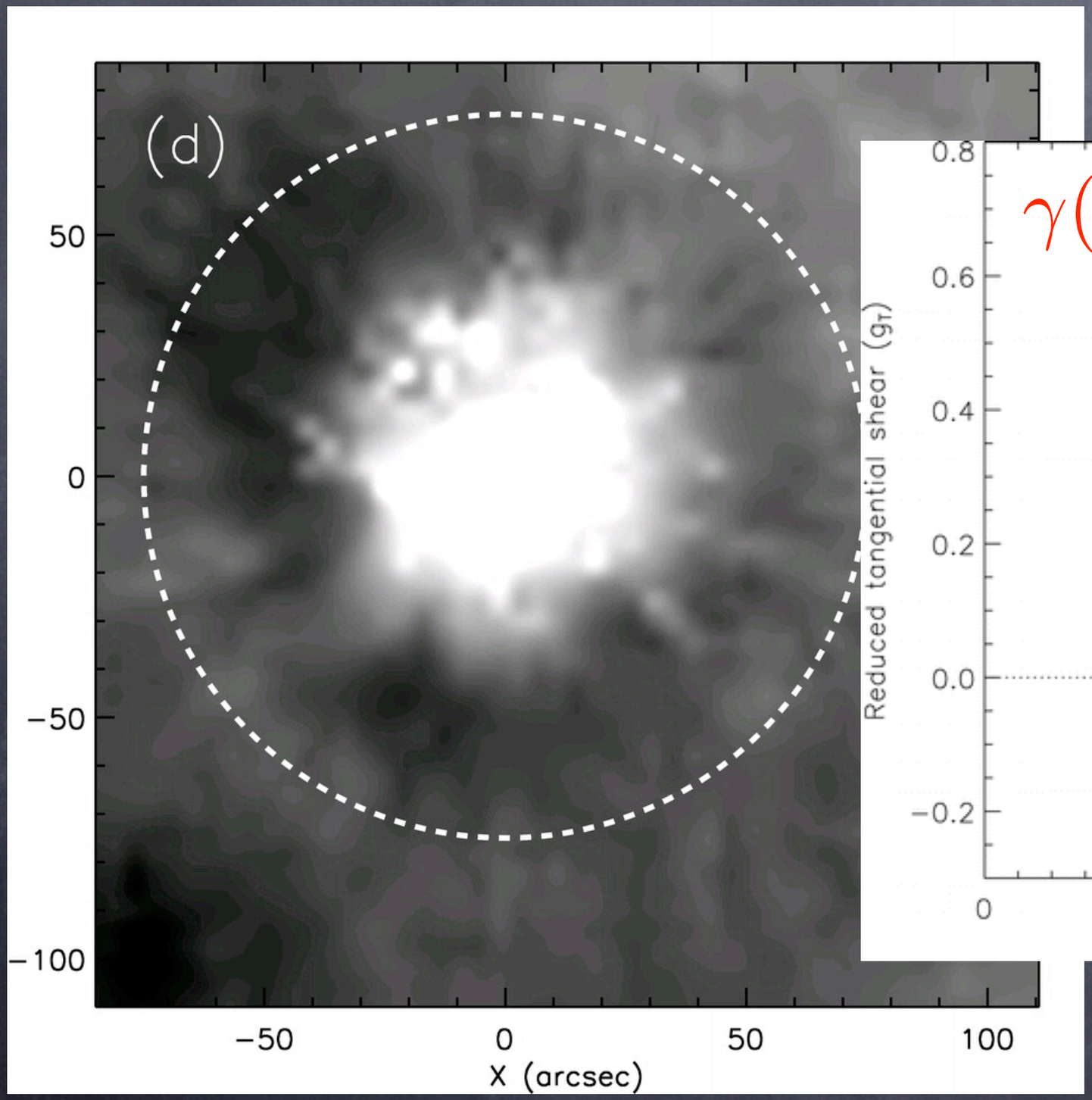
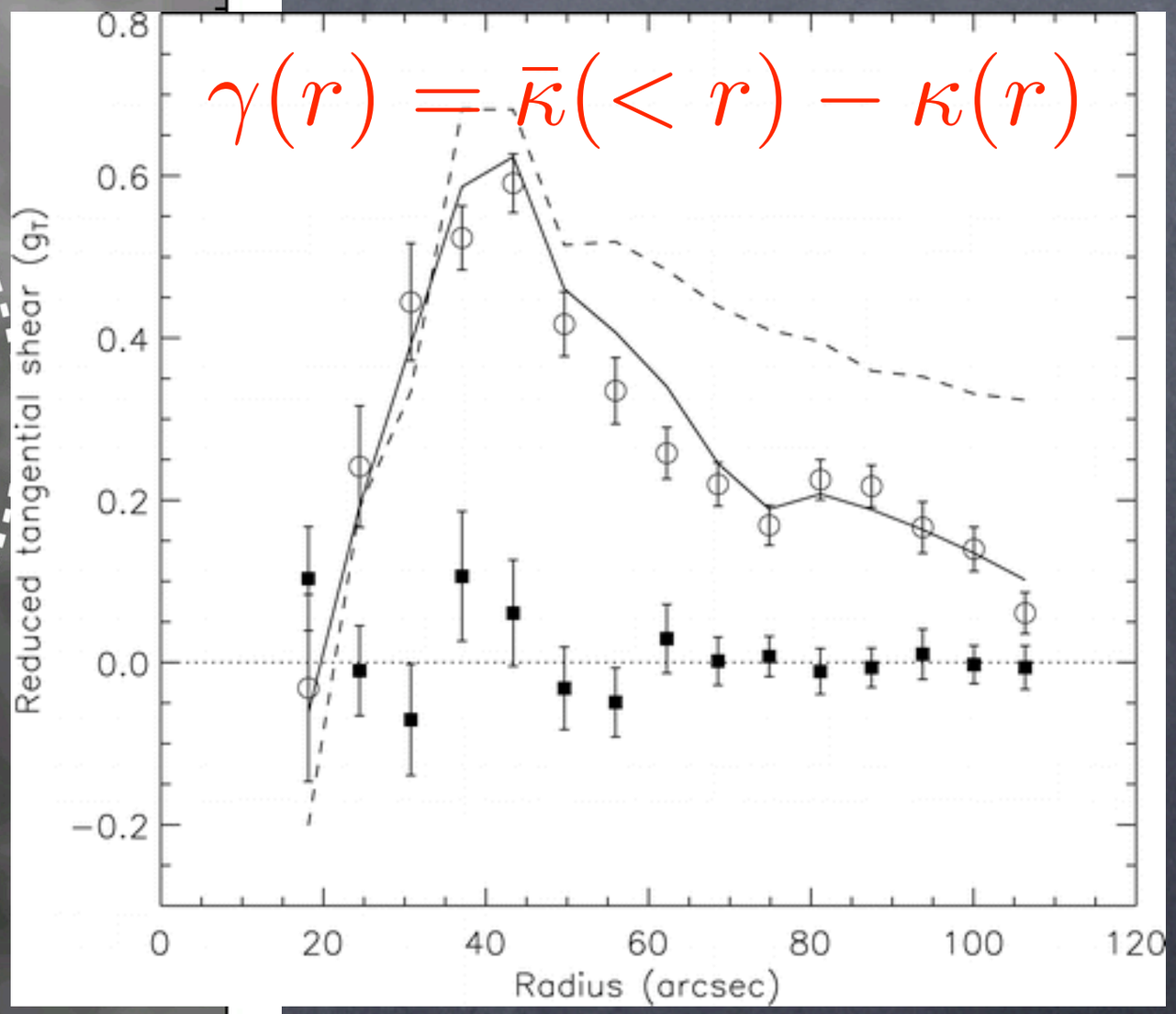
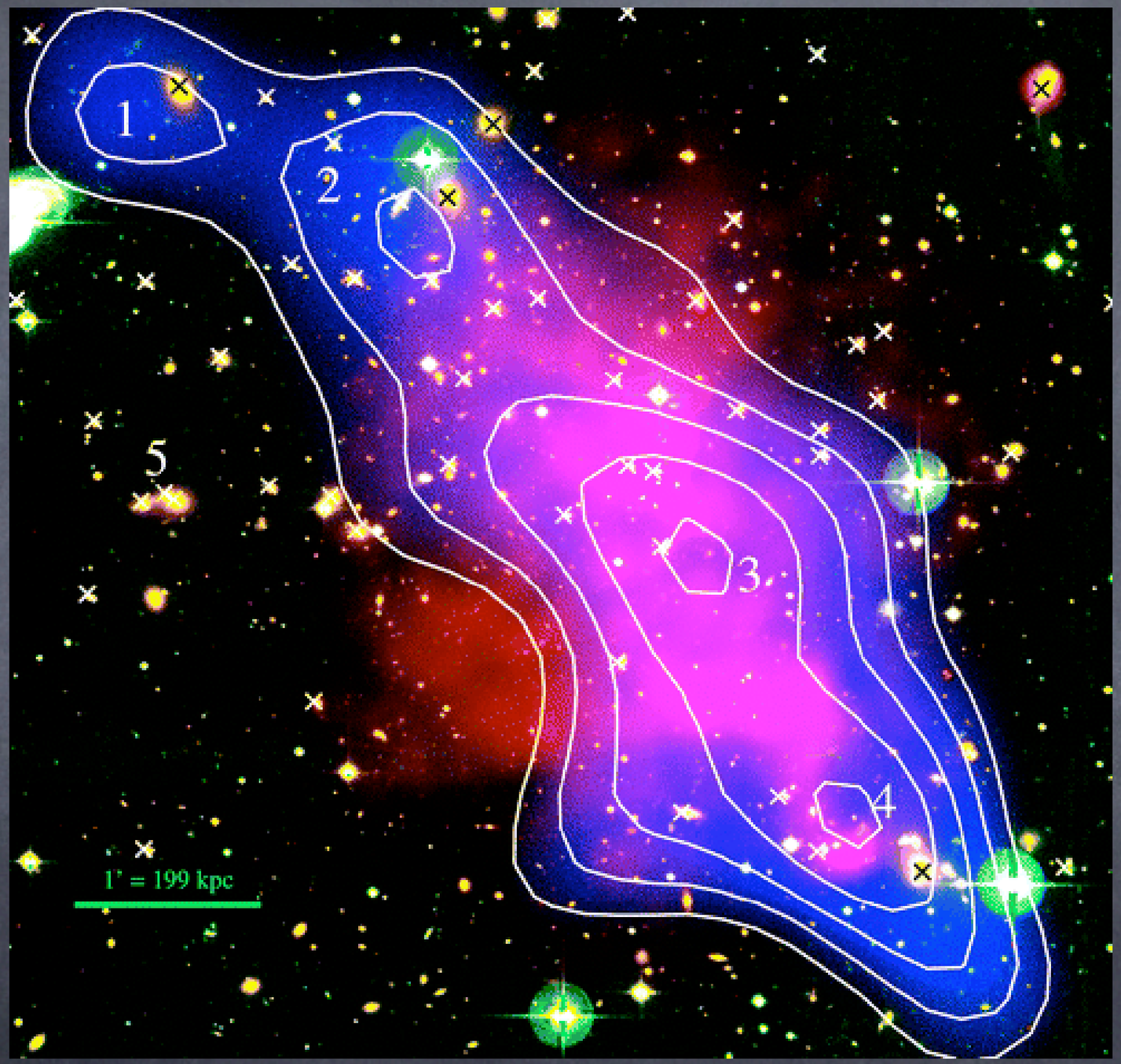


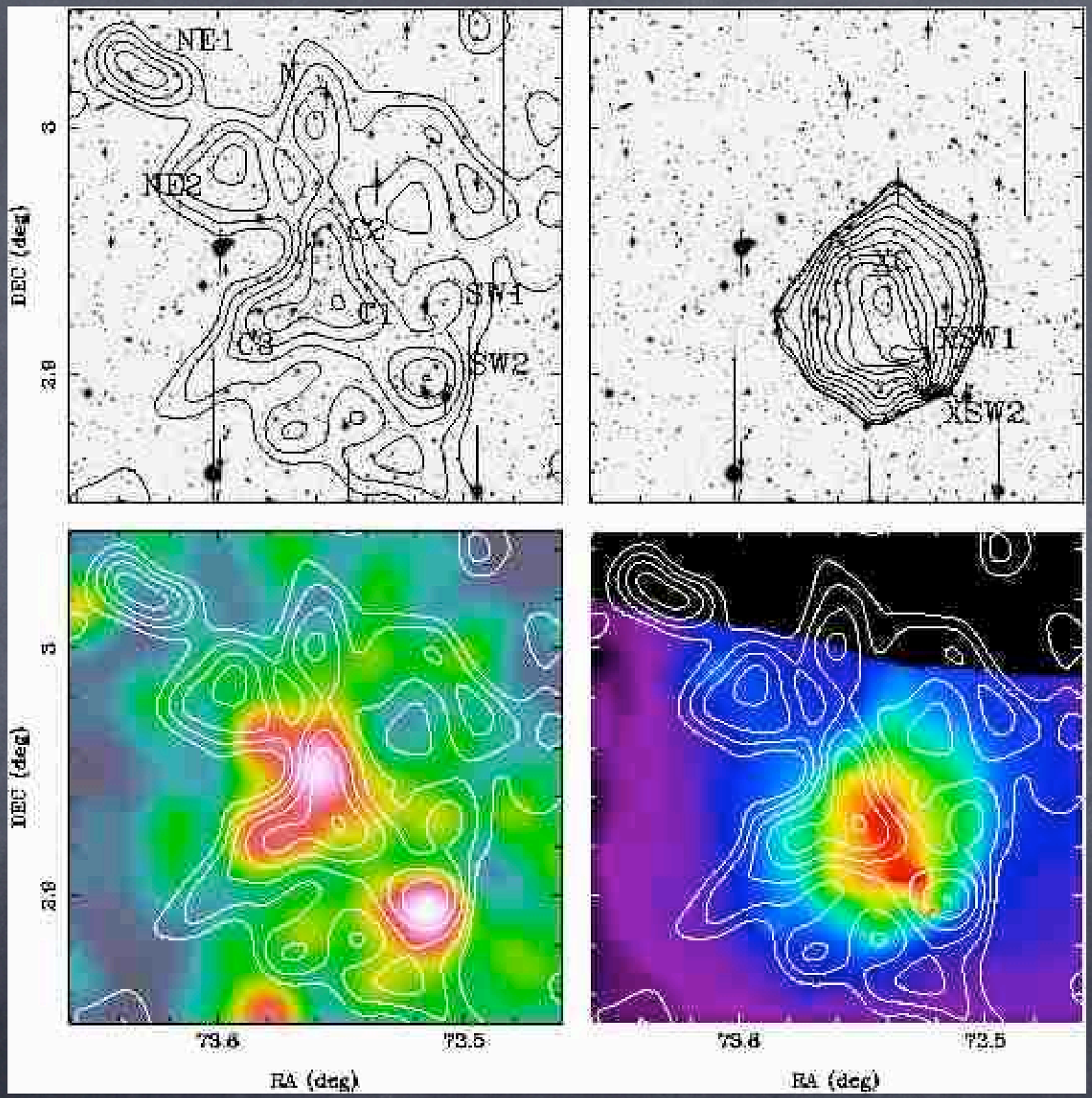


Jee et al (2007)

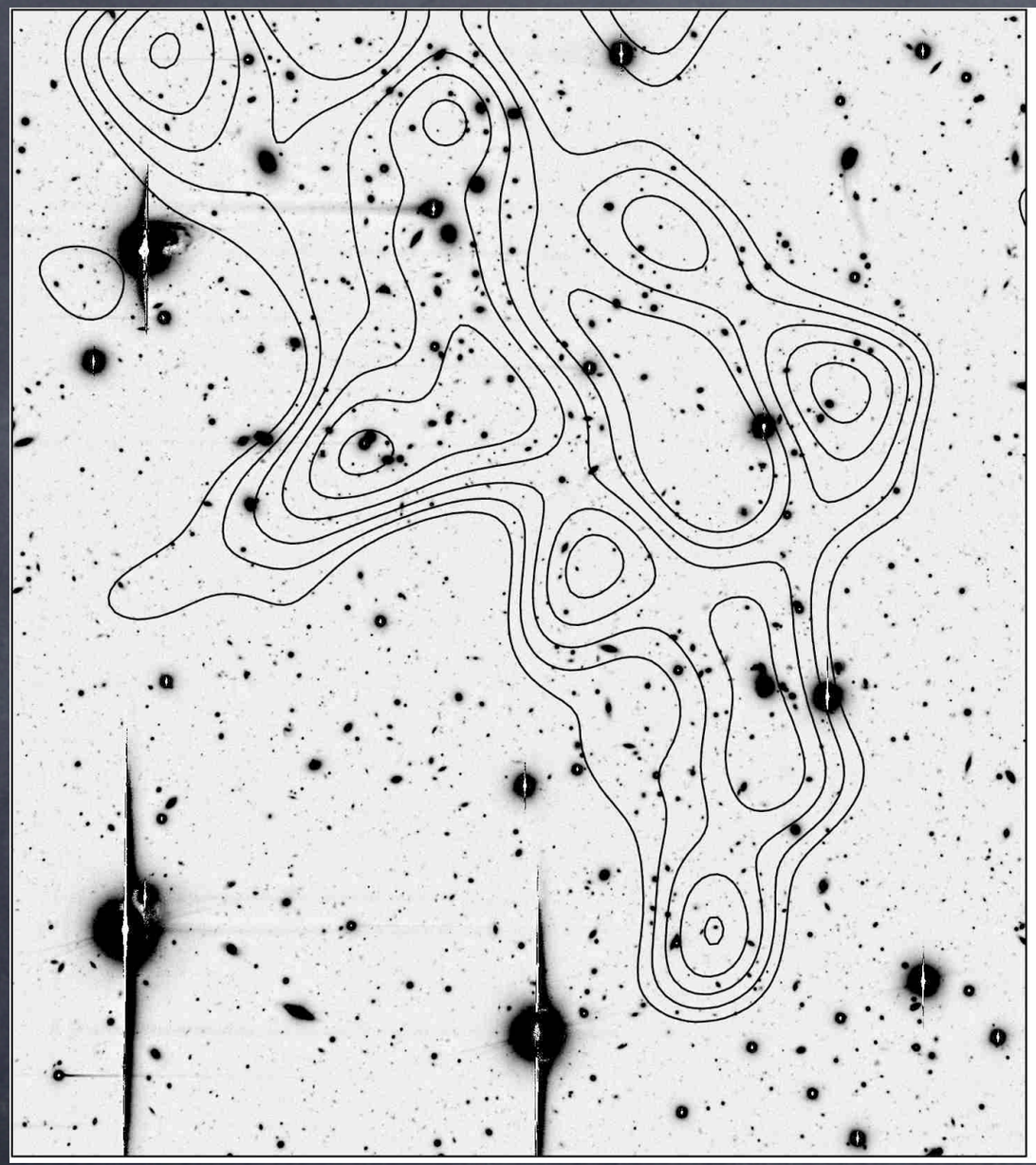
A Dark Core?

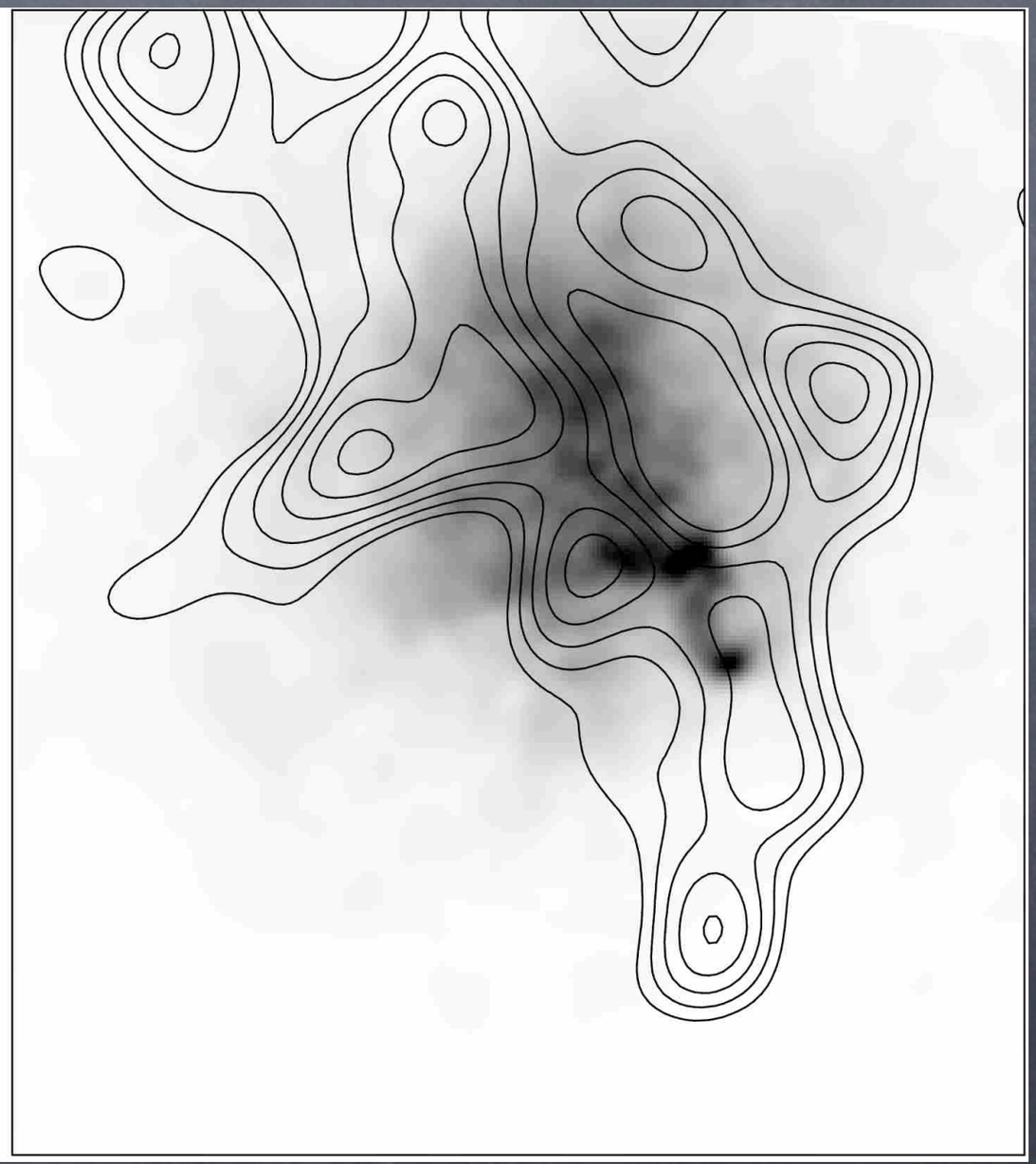


Mahdavi et al (2007)



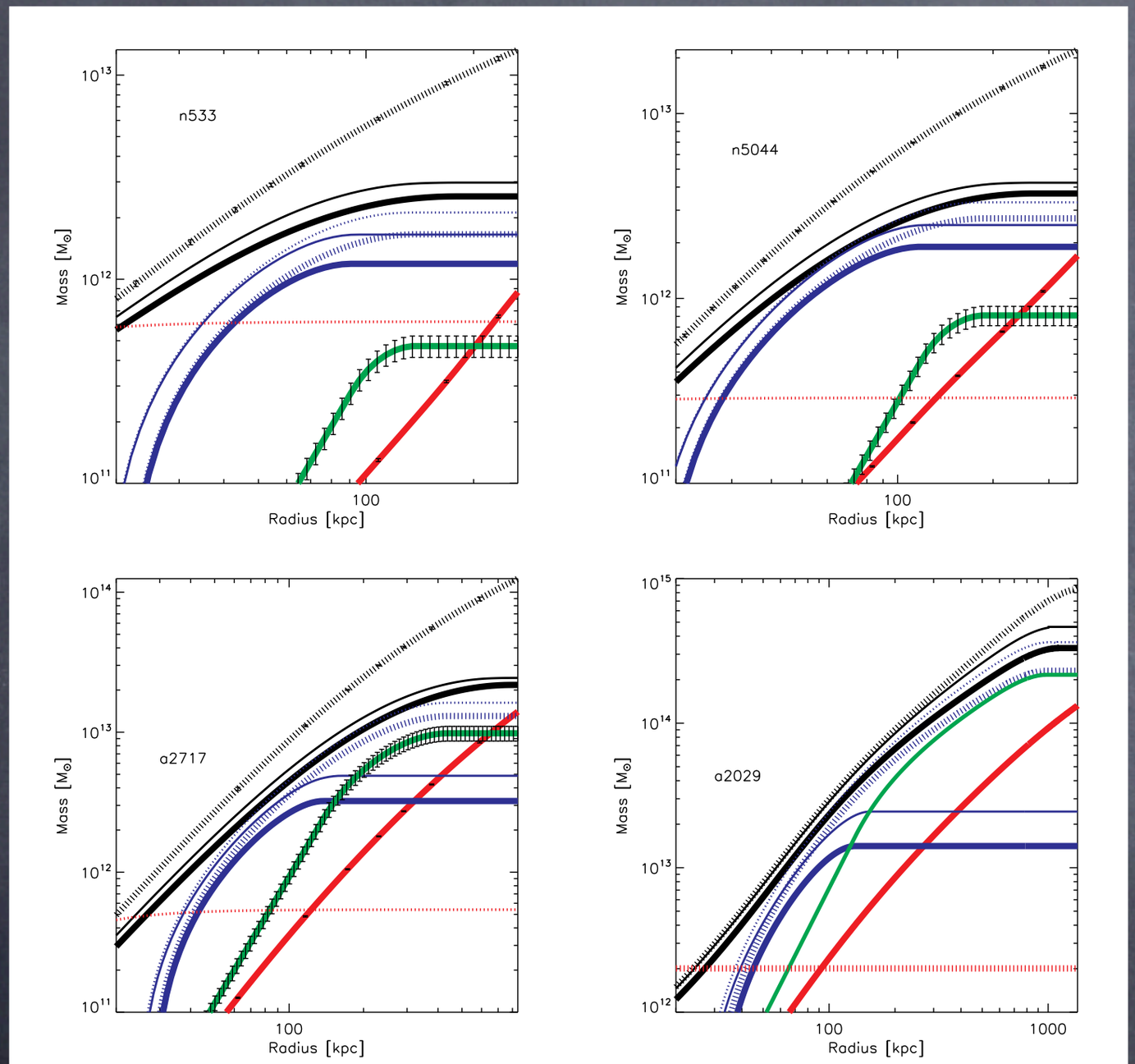
Okabe and Umetsu (2007)





Clowe et al (eventually)

MOND vs DM in groups



Angus, Famaey, & Buote (2008)

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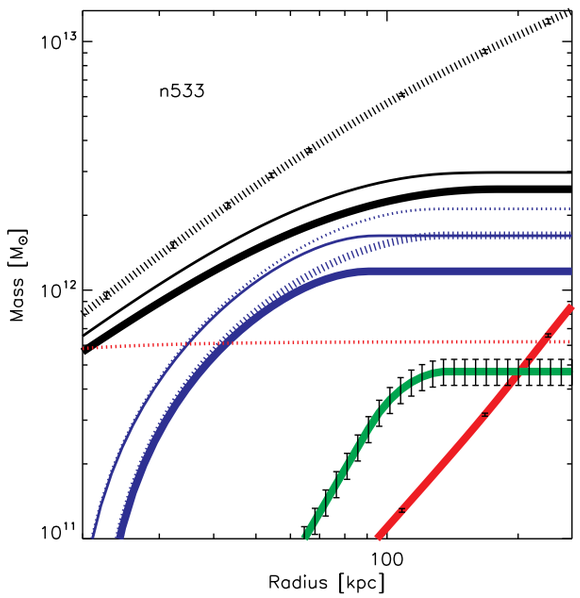

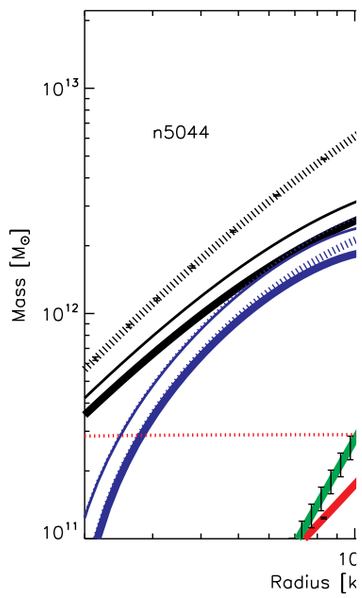

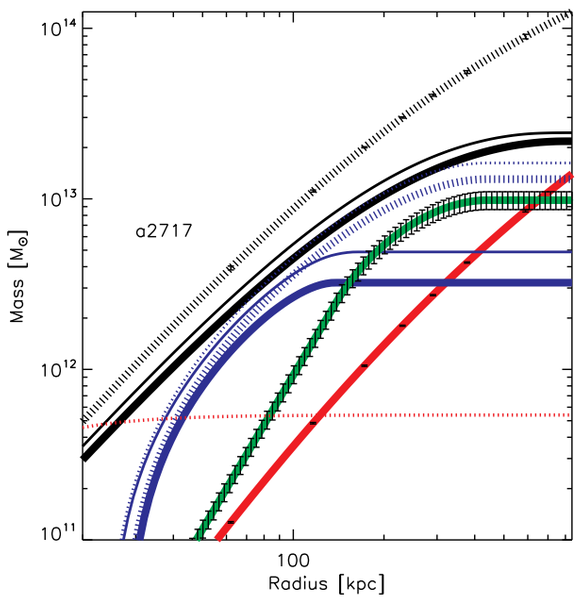

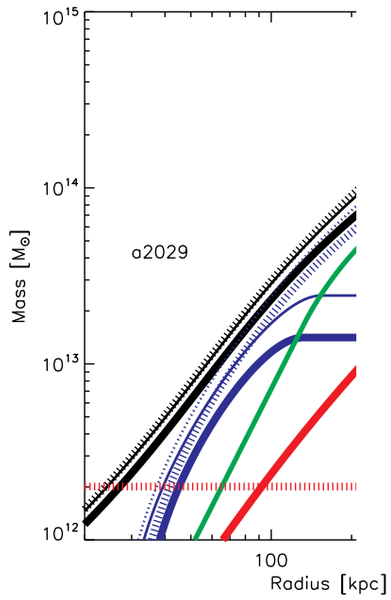

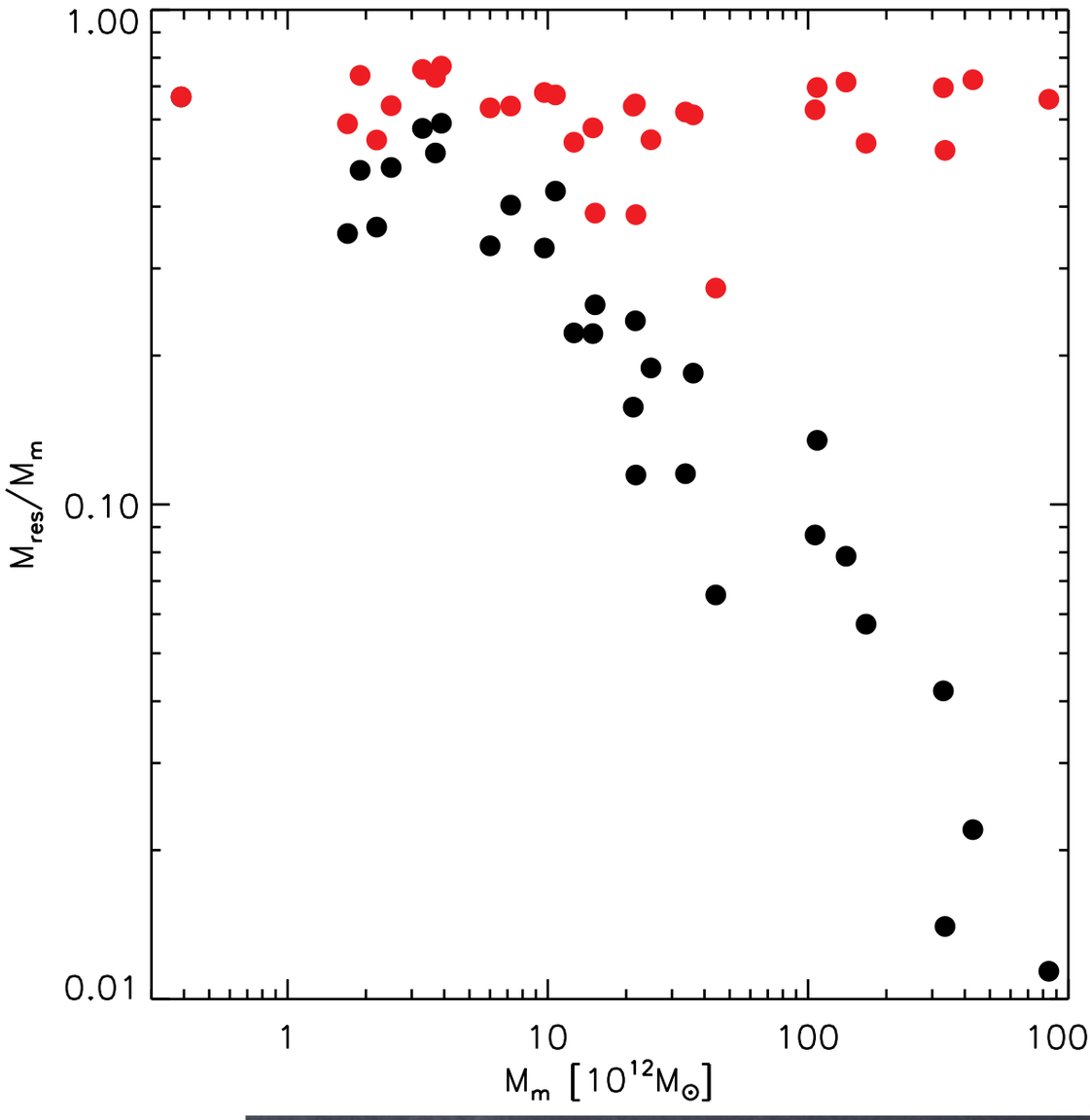

Angus, Famaey, & Buote (2008)

MOND on the outskirts of galaxies

- Hoekstra, Gladders, & Yee (2004) found that the galaxy-galaxy lensing signal around massive galaxies is not circular at large radius (as predicted by MOND without DM)
- Result confirmed Parker et al (2007) with CFHTLS galaxy-galaxy lensing
- Tian, Hoekstra, and Zhao (2008) find that the galaxy-galaxy lensing signal increases with galaxy luminosity faster than MOND would predict (and faster than MOND + neutrinos)

Mili-lensing

Substructure in the lensing galaxy can produce microlensing type effects 1 of the multiple images.

Measurement of these effects can constrain amount of substructure in galaxies and the sizes of the black holes and accretions disks in the quasar lenses.

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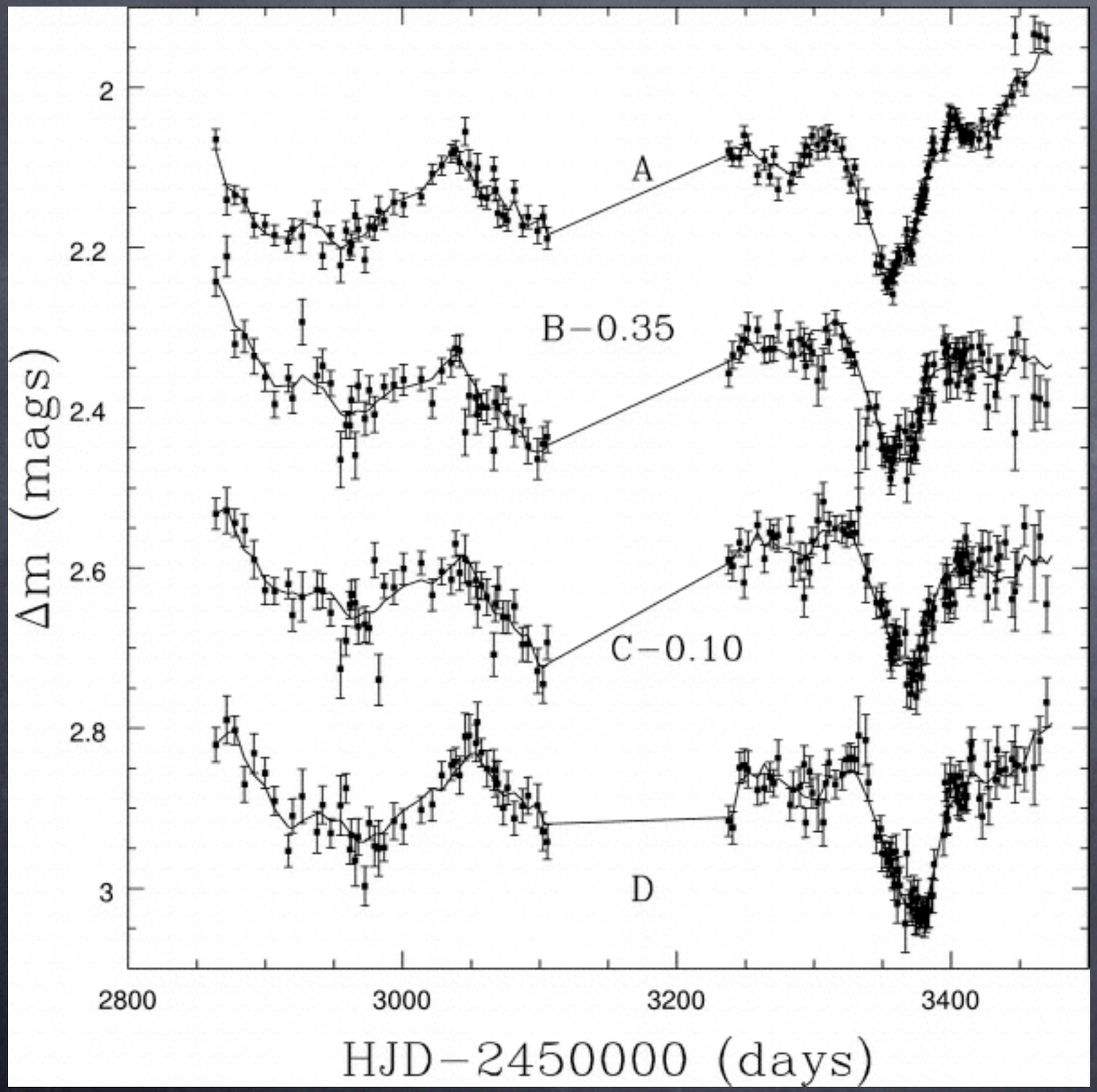

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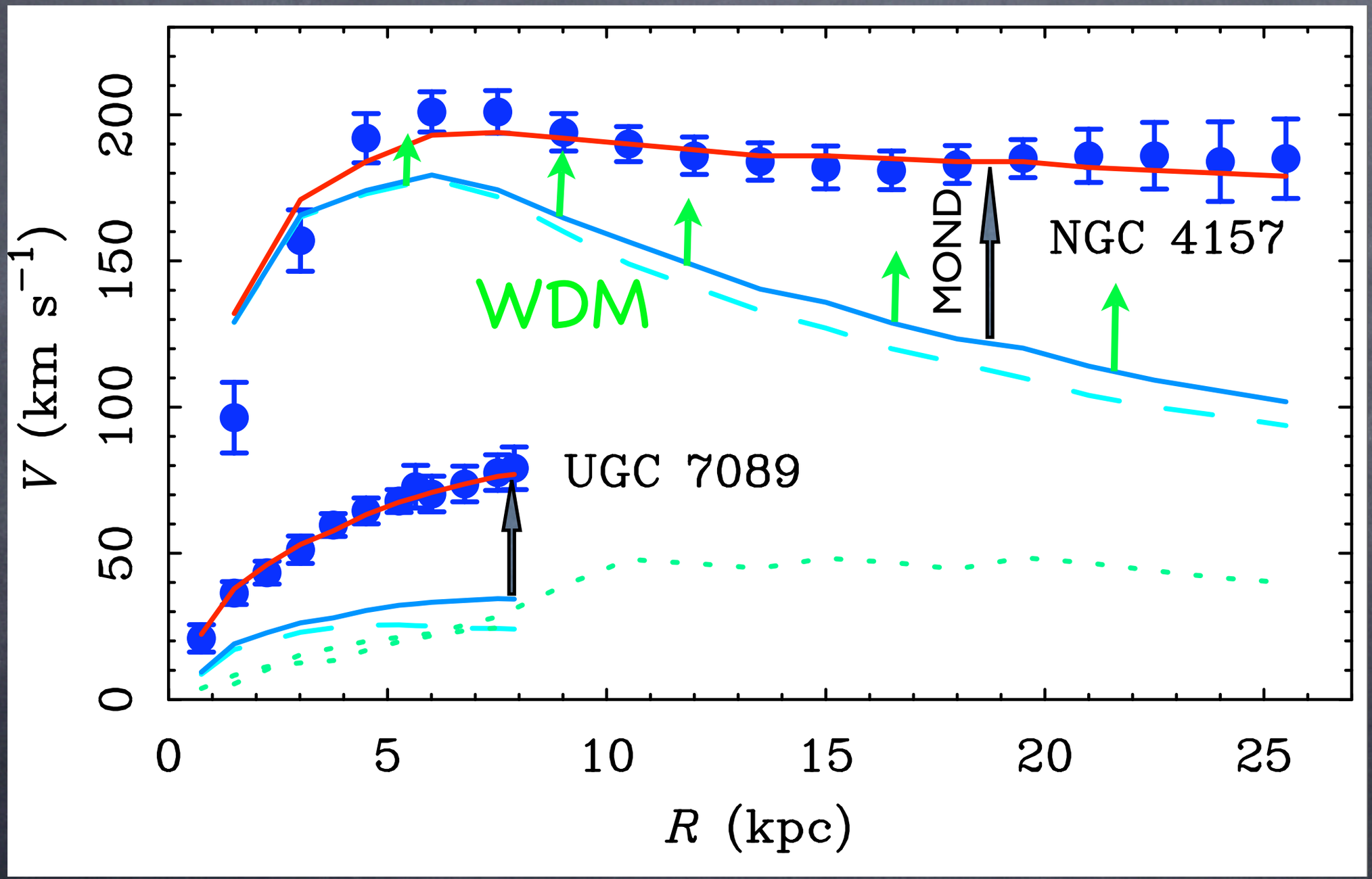

Figure stolen from Stacy McGaugh

Conclusions

- MOND (and all alternative gravity models) require twice as much DM as visible baryonic matter, including a large non-neutrino component
- Ring and DM bump are too low of significance detections to base any conclusions about gravity or DM models off of
- MOND may need LWDM to account for lensing and X-ray data on the outskirts of massive galaxies -> possible conflict with inner rotation curves of galaxies